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Formability limit diagrams of extra-deep-drawing steel at elevated temperatures

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Abstract

In the present work forming limit diagrams for extra deep drawing steel at room and elevated temperatures have been determined experimentally by conducting stretch forming operations using designed and fabricated warm forming tooling setup. With the help of FLDs formability of EDD steel has been analyzed and co-related with mechanical properties like strain hardening coefficient (n) and normal anisotropy (r⁻).Material properties of EDD steel are calculated at various temperatures and effect of these properties like work hardening exponent (n) anisotropy(r⁻) and strength of the material are co-related by FLDs at various temperatures.

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Keywords: EDD steel, FLD, warm forming, Stretch-forming:

1. Introduction

Sheet metal forming is defined as ability of material to deform plastically or converting the sheet metal into a required shape without necking or crack. The properties of material and process parameters have a vital role in all of the sheet metal forming operations. The material properties such as yield strength, elastic modulus, anisotropy, strain hardening coefficient etc. and the process parameters as punch & die geometry, lubrication, punch speed and blank holder force determines the forming quality of the process. Therefore, a suitable material selection and determining optimum forming parameters is a must for a successive sheet metal forming process. The common sheet metal forming processes [Marciniaket al.2002] can be used to achieve the simple to complex parts are blanking and piercing, bending, stretch forming, extrusion, stamping, deep drawing, tube forming, fluid forming, coining and ironing. Sheet metal parts (automobile, aerospace applications) which are produced by stretch forming can be stiff and have a good strength to weight ratio. So however for a given process and deformation geometry, the forming limits vary from material to material. The basic concern is whether the desired deformation can be accomplished without failure of the work piece. Therefore, the research and development studies are still being made in order to evaluate the forming limits of the sheet metals.

To control the sheet metal forming operation without failure, a diagram is used in which the fracture, critical and safe forming regions are shown. This diagram is known as the Forming Limit Diagram (FLD). In research studies and sheet metal industry it is widely used and considered as one of the most important tool to determine the formability of sheet metals. Every sheet metal has its own forming limit diagram which determines its formability, strain limit and forming regions. Forming limit diagram is a representation of the critical combination of the two principal surface major strains and minor strains which localized necking instability is observed. For varying strain ratios, from pure tension-tension, to tension-compression regions, the forming limit curve is plotted. When the strain ratio is positive (minor strain is positive), it means stretching is observed. In case of negative strain ratio (minor strain is negative), one can conclude drawing is observed. It should also be noticed that the strains plotted are true strains. In order to analyze the sheet metal instabilities and construct the FLD, various experimental and theoretical approaches exist. Several types of experimental testing procedures are presented in literature in order to obtain the forming limit diagrams of different materials like, aluminium, copper, brass, steel and its alloys. Keeler test, Hecker test, Uniaxial tensile test, hydraulic bulge test, punch stretching test, Marciniak test and Nakazima test are some of the experimental procedures are used to determine the formability of material. Keeler test[3] consist the use of punches of different radius to obtain different stress states to obtain the positive ($\varepsilon 2>0$) range of FLDs.

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The main disadvantage of the test is the need for high amount of experimental work. By varying the friction regime, using the same die and specimen geometries the positive range of FLD can be obtained by Hecker test [Hecker.SS.1975]. In uniaxial tension test, the frictional effects are eliminated and only the negative range of FLD (ε_2<0) can be obtained. The hydraulic bulge test is performed to determine only the positive range of FLD (ε_2>0) by changing the shape of the elliptical dies to obtain different strain paths. The frictional effects are also eliminated in this test. Next, punch stretching test can be used to obtain the FLD. In this test the specimen is clamped between a die and a blank holder and stretched by a hemispherical or elliptical punch. Different strain paths are obtained by varying the specimen geometries. Then, in Marciniak test a hollow punch is used. There is an intermediate part which has a circular hole is placed between the work piece and the punch. The aim is to obtain the tearing at the planar bottom section of the cup, otherwise cracks occurs between the cylindrical wall and the bottom. Complex geometries of punches and dies are required and there is a limitation for the positive range of the FLD. By using different specimen geometries and intermediate parts full range of FLD can be obtained. In Nakazima test stretching the specimens with hemispherical punch and a circular die for varying widths, different strain paths can be obtained. Finally Hecker's simplified technique is most widely used experimental procedure mainly involves stretching the grid-marked samples by hemispherical punch to failure or onset of localized necking and measurement of strains.

From all of the above tests, Hecker's simplified technique [Hecker.SS.1975] seems to be the most powerful and advantageous test because the tools used for the test and the geometries of the specimens are simple, and full range of the FLD can be determined. Today, it is widely used in industry and sheet metal testing laboratories in order to evaluate the forming limits of the sheet metals. In addition to these experimental studies, theoretical and empirical studies have also been performed to evaluate formability of the sheet metals. Several researchers have been studied on the prediction of FLDs by analytical and theoretical methods. Formability of the material is affected by various factors like thickness of sheet, forming speed, lubrication condition, temperature, anisotropy, and strain hardening.[D Ravi Kumar.2001] determined the formability limit diagrams for aluminium killed EDD steel sheets of various thickness and shown that the level of the FLD was increased significantly with the sheet thickness.[Tetsuo Naka et al.2001] investigated experimentally by performing stretch forming tests at different forming speeds (0.2 to 200m/min) at different temperatures ranging from 423^0K to 573^0K and reported that forming speed and temperature effects on formability of Mg alloy sheets. The limit strains increases with decreasing speed at a temperature range (423^0K to 573^0K).[Ozturk et al.2005] investigated on effect of lubrication on formability and reported that the lubrication between blank and punch decreases the frictional forces ,increases strain distribution and hence delayed the local thinning. Previous studies revealed that stretch formability of AZ31 sheets was improved at elevated temperature [HUANG Guang-sheng et al.2011,Tetsuo Naka et al.2001,Yasumasa Chino et al.2007].Initially some empirical models [A.K.Ghosh.1975,Goodwin GM.1968,Hecker.SS 1975,Keeler SP.1965] were developed. Then, there occurred a need for the more accurate theoretical methods. Theoretical and numerical determination of FLDs is commonly based on localization criteria. Localization criteria based on the maximum load principle [Babanicet al.2000,C.EDreyerbet al.2010,Marciniak.Z.1984,Narayanaswamy.R et al.1993,Narayanaswamy et all.2008,S.Ahmad et al.2009,S.B Kim et al,2010] exists in literature with their drawbacks and limitations. The suitability of the proposed methods has been investigated for various materials and the new approaches are still being developed with the advances in technology.

In the present work, stretch forming operation is performed on one mm thickness EDD steel specimens of length 110mm, and varying the width from 110mm to 20mm (Hecker's simplified technique).For stretching the EDD steel sheets suitable die, hemispherical punch and hydraulic press were used. The formability limit diagrams and fracture limit diagrams were determined at room temperature,150^0C,300^0C and 450^0C for EDD steel sheets. Then these formability limit diagrams and fracture limit diagrams were analyzed.

2. Experimental setup:

A hydraulic press of capacity 20 tonne was used for stretching the EDD steel specimens Fig [1]. Suitable die-set Fig [3]with draw-beads was made with Inconel-600 material to minimize the expansion during heating the die. This design for initial experiments was taken from the studies of Ravi Kumar (2001). But material chosen for dies was different. In this study a nickel based material is used to avoid the design change by increasing the temperature of dies. Since the material is hard, the machining was performed using electrochemical machining. Electro chemical etching machine was used for printing the grid pattern on the specimens using the stencil. Circles of 5mm diameter were printed on the blank sheet. Largest size specimen used was 110X110mm and its width was decreased in the steps of 10mm.For heating the blank, the lower die was heated by providing induction coil around it fig [2]. This die is heated to a required temperature so that stretch forming operation can be performed at a particular temperature. This temperature was measured using pyrometers attached to the machine.

Fig-1 Hydraulic press for Stretching

Fig2-Lower die with heating for Stretching

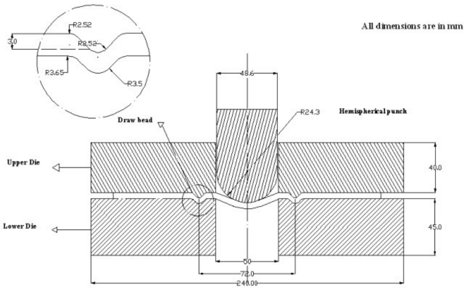


Fig-3: Punch &Die set for Stretching (Ravikumar-2002)

3. Experimental procedure

3.1. Chemical composition &Tensile test

Table1.Composition of EDD Steel

Element	C	Si	Mn	S	P	Cr	Sn	Cu	Ni	Mb	Fe
% of weight	0.048	0.83	0.39	0.024	0.019	0.027	0.004	0.019	0.054	0.028	Rest

The chemical composition of EDD steel sheets used in the experiments was found out by spectrometry and the same is presented in Table 1.Tensile tests were carried out by using electronic universal Testing machine of 5 tonne capacity. The samples were prepared by cutting the EDD sheets along three different directions namely 0◦, 45◦ and 90◦ to the rolling direction of the sheets. The load versus extension data were obtained from these test. The strain hardening exponent (*n*), the plastic strain ratio (*r*) (which is the ratio of the width strain to the thickness strain) and planer anisotropy ($\bar{r}$) which are important factors that indicate the formability of the sheet metals were determined from the tensile tests. Using the equation $\sigma = K\varepsilon^{n}$, where σ is true stress and ε is true strain *K*, strength coefficient was found out. $\bar{r}$ Values along three directions namely parallel (0^0), diagonal (45^0) and perpendicular (90^0) to the rolling direction were found out using tensile test. The normal anisotropy $\bar{r}$ and the planer anisotropy (Δr) were calculated from the r values determined along three directions namely parallel (0^0), diagonal (45^0) and perpendicular (90^0) to the rolling direction using the following expressions:

$$r = \frac{r0 + r90 + 2r45}{4}$$

$$\Delta r = \frac{r0 + r90 - 2r45}{2}$$

3.2. Stretch forming tests

The FLD was evaluated following Hecker's simplified technique [6]. In this method, mainly the experimental procedure involves three stages

1) Grid marking on the specimen sheets.
2) Stretching the grid-marked samples to failure or onset of localized necking or safe
3) Measurement of strains.

Grid marking on the EDD steel sheet samples was done using a non-contacting grid of 5 mm diameter circles. The grid pattern was etched on the samples using an electro-chemical etching machine. Punch-stretching experiments were carried out on a 20 tonne (20t) capacity hydraulic press. The punch-die assembly was designed and fabricated depending on the thickness of the sheets. A typical punch-die assembly used in the experiments is shown in Fig[3]. The sheet samples were subjected to different states of stain, i.e. the tension-tension zone, plane strain and the tension-compression zone by varying the width of the sample. In this method samples were cut using sharing machine. The length of the blank was 110 mm and width was varied between 110 to 20 mm insteps of 10 mm. For each blank width, at least five specimens were tested for each temperature to get maximum number of data points. To obtain the maximum values in the magnitude of the negative minor strain, uniaxial tension tests were also done using grid-marked of localized specimens. The blanks were stretched to before necking i.e. safe, the experiments were stopped at the time of onset of localized necking in some cases and continued till fracture in other cases. The circles on the sheet samples became ellipses after stretching, falling into safe, necked and failed zones. The major and minor diameters of the ellipses were measured using a travelling microscope with an accuracy of 0.01mm.Major strains and minor strains were calculated in three regions.FLD was drawn by plotting the minor strain in abscissa and corresponding major strain in ordinate and by drawing a curve which separates the safe region from the unsafe region. The fracture limit and forming limit curves were drawn by connecting the fracture strains for various blanks of a EDD steel sheets. The accuracy of the FLD lies well within a band of ±2% in the engineering strain values.

4. Results and discussion

4.1. Chemical composition tensile properties

The tensile parameters namely strain hardening exponent (n) and strength coefficient (K) of various steel sheets taken for study obtained from the tensile tests are tabulated in Table 2

Table 2:Mechanical properties of EDD steel

TEMPERATURE (0C)	UTS (M Pa)	YS (MPa)	STRAIN AT YS	ELONGATION (%)	STRENGTH COEFFICIENT (K) (MPa)	WORK HARDENING EXPONENT (n)
25(RT)	337	202	0.0222	44	677	0.304
150	304	188	0.0291	35	577	0.274
300	294	184	0.0314	29	548	0.289
450	329	216	0.0582	39	684	0.261

Singh (2010) investigated the properties of EDD steel at various temperatures using 5tonne electronically controlling UTM. For this material it was observed that serrations in the work hardening regime it start appearing between 350^{o}C to 400^{o}C.It was also observed that there was slight increase in the properties like strength coefficient work hardening coefficient and strength of material in this temperature range. It is because of presence of silicon etc which increases the dislocation density within the material due to phenomena of dynamic strain regime. In the present investigation the formability limit diagrams were constructed in this range to see the impact of serrations on the formability.

4.2. Formability Limit Diagrams

The forming limit and fracture limit diagrams for different temperatures are shown in Figs 4-7. The strain combinations above the FLD line will lead to fracture and those below the line will produce safe region in the drawn cup

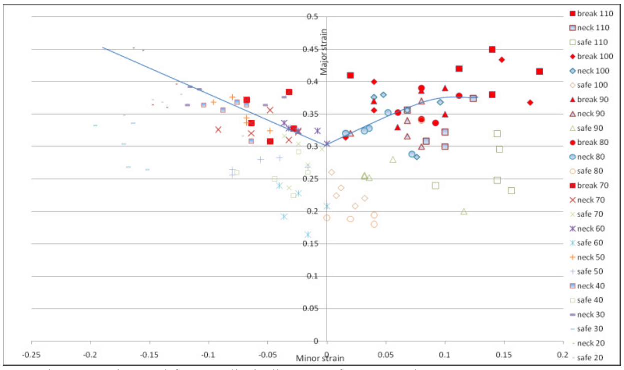


Fig:4 Forming and fracture limit diagram of EDD steel at room temperature

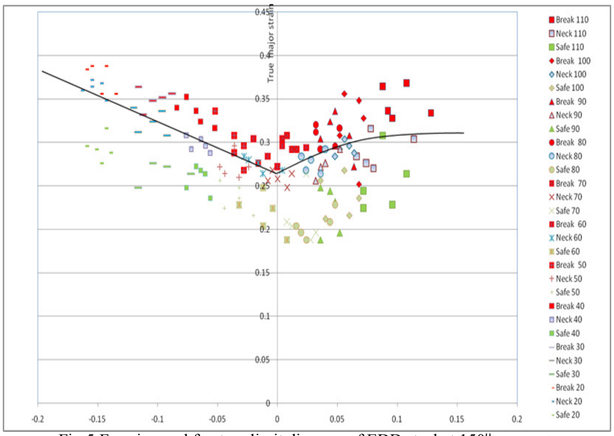


Fig:5 Forming and fracture limit diagram of EDD steel at 150^{0}temperature

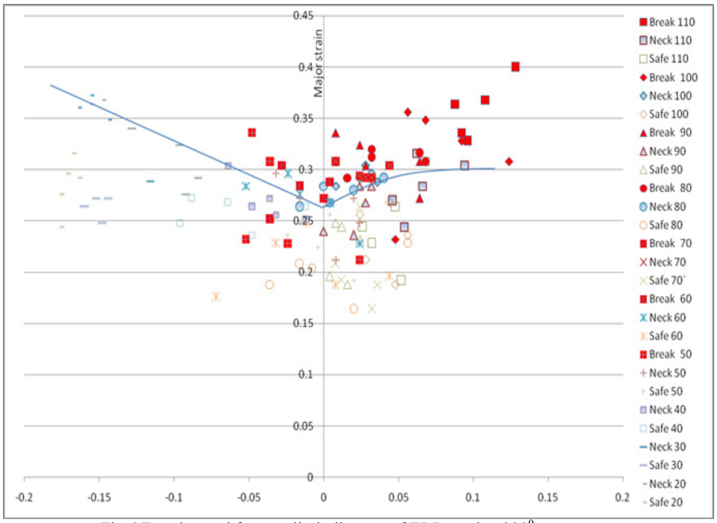


Fig:6 Forming and fracture limit diagram of EDD steel at 300^0temperature

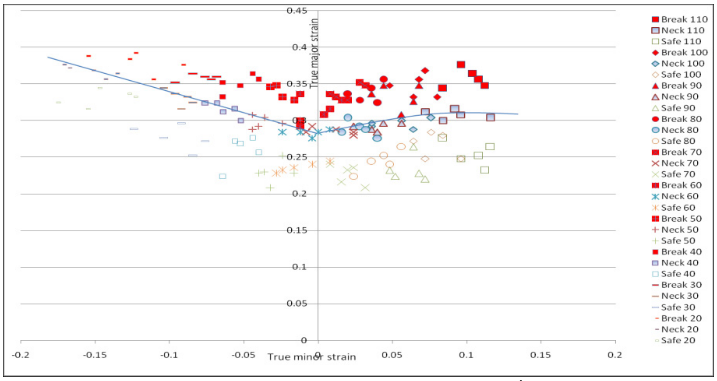
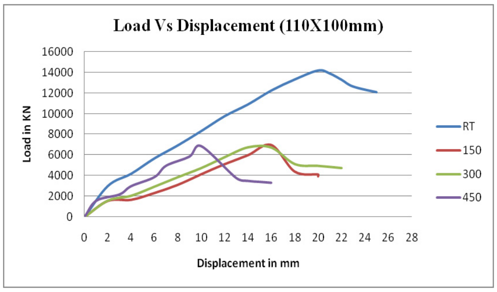
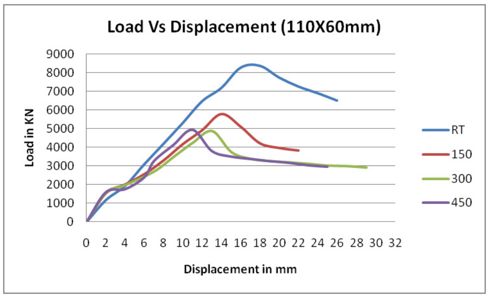


Fig:7 Forming and fracture limit diagram of EDD steel at 450^0temperature

FLDs were determined experimentally for the EDD steel sheets by following Hecker's simplified technique are shown in Fig:4-7.The above FLDs shown that stretchability of sheet metal is strongly influenced by the value of strain hardening exponent (n).The n values of EDD steel sheets are shown in table2.From the table it can be seen that the values obtained from true uniform strain in tensile test agreed well with the FLDs obtained at room temperature,150^0C ,300^0C and 450^0C mainly in plain strain region. The formability of EDD steel at room temperature, 150^0C, 300^0C and 450^0C temperatures are consistent with expectations based on the uniaxial tensile properties. The effect of temperature on EDD steel sheets is observed the level of the FLD is clearly seen, particularly at the plain strain condition. The level of the FLD decreased with increase in sheet temperature, which is approximately coincident with strain hardening exponent (n) at each considered temperature. But the level of FLD was increased at temperature of 450^0C irrespective of increase in temperature. It is because by increasing the temperature further there was effect of sensitivity index and also dynamic strain regime starts appearing in the material near this temperature [Singh et. al. 2010].It can be seen the table 2 that at 450^0C there is increase in strength, strength coefficient and relative increase in the work hardening exponent.

It can be seen from these FLDs that as the temperature increases, strain data points in the neck and also in the fracture region, there is a downward trend in these data points towards biaxial stress line. It is primarily because as the temperature increases, there will be decrease in the mean flow stresses and lesser amount of load will be required to deform the material. This phenomenon can be seen in the load- displacement graphs presented in Fig. 8 that by increasing the temperature of specimen, there is decrease in the load requirement in all the samples. There is slight increase in the load at 450^0C as compared to 300^0C because of dynamic strain regime where there is an increase in work hardening coefficient and as a result of that strain data points in the biaxial stress region is having slight upward trend. It can be seen from load-displacement graphs that by decreasing the width of strip, similar trend in the data was observed.





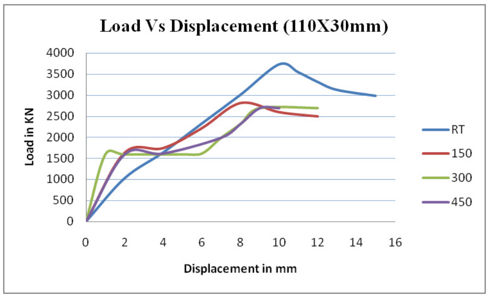


Fig. 8: Load Vs displacement diagrams for various test specimens and at different temperatures

5. Conclusions:

In order to understand the formability of EDD steel at elevated temperature the formability limit diagrams were constructed at different temperatures using Ni based super alloy dies.EDD steels are naturally formable at room temperature but their formability increases by increasing the temperature primarily because of decrease in the mean flow stresses .Specially at 450°C the material exhibits low formability due to the dynamic strain regime and same thing is experienced in the formability limit diagrams. It was seen from FLDs that for a substantial portion of sample plain strains were observed at all the temperatures

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